中國科學院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Mass production and characterization of 3-inch PMTs for the JUNO experiment

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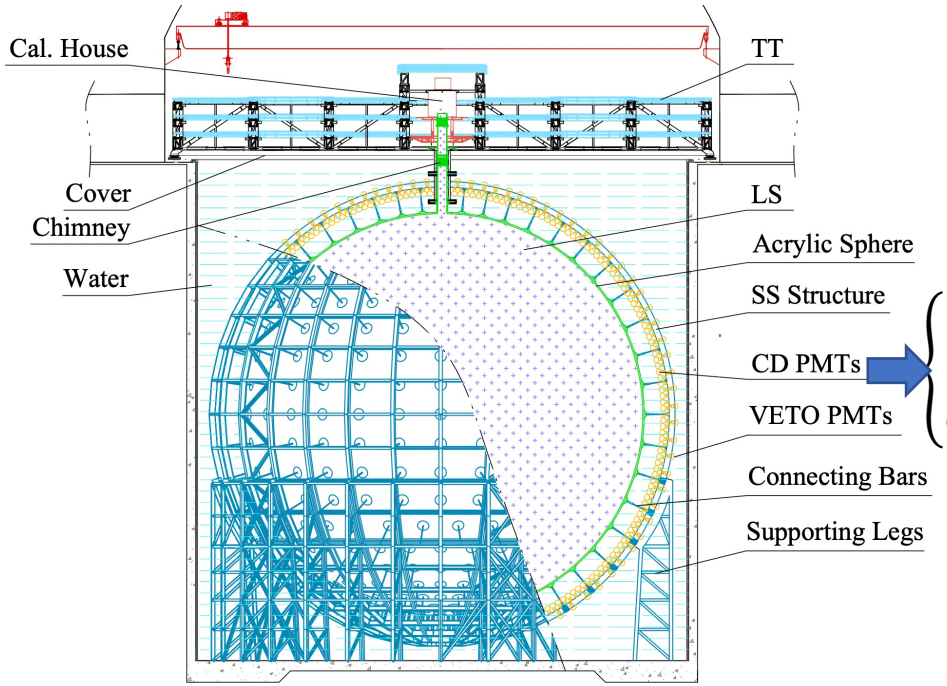
On behalf of JUNO collaboration

Technology and Instrumentation in Particle Physics
2021/5/27

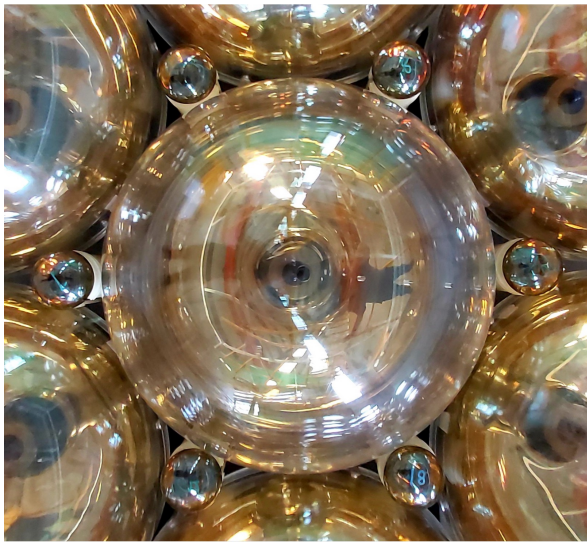
Nuclear Inst. and Methods in Physics Research, A 1005 (2021) 165347

Jiangmen Underground Neutrino Observatory

- JUNO: a multipurpose neutrino experiment in Guangdong, China
  - 20 kton liquid scintillator, 3% energy resolution @ 1 MeV, 700 m underground, ~ 53 km baseline
  - Neutrino mass ordering, precision measurement of oscillation parameters, supernova, geo-, solar, … neutrinos

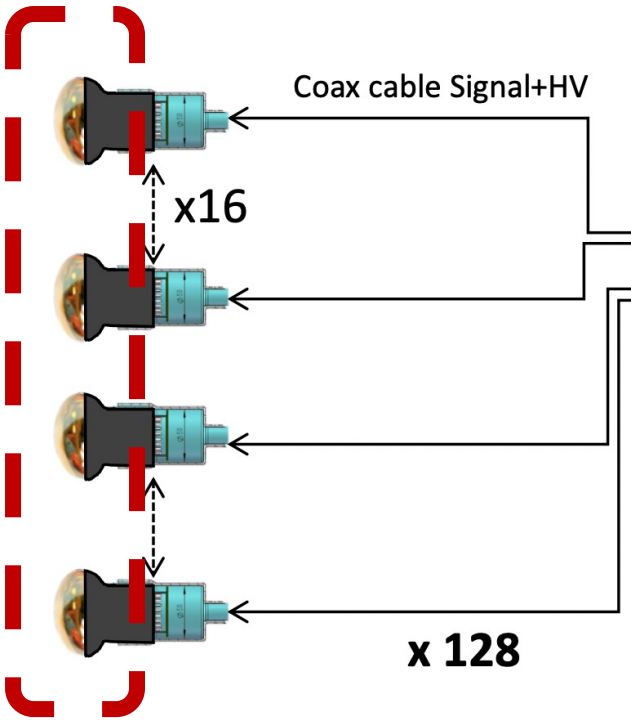


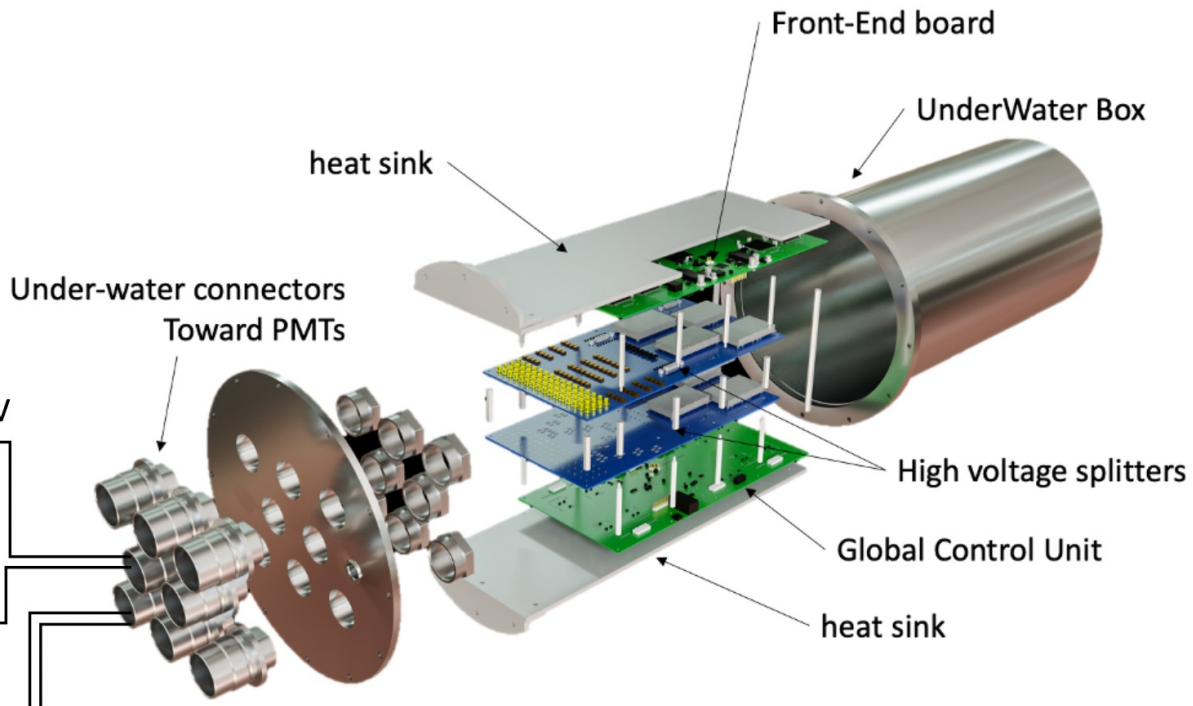
$17,612\ 20''PMTs$
$\mathbf{25,600\ 3''PMTs}$
$Coverage = 77.9\%$



sPMT system in JUNO

3-inch PMT:
production concluded



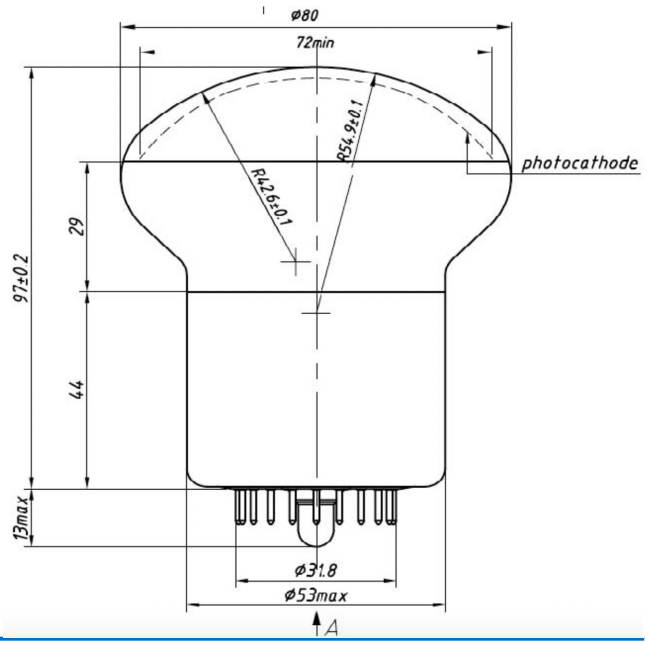


Same HV will be set for 16 PMTs

200 underwater electronics boxes in total

3-inch PMT XP72B22 in JUNO

- XP72B22: a JUNO custom design
  - Upgrade of XP72B20 (shape of glass bulb)
  - Produced by Hainan Zhanchuang Photonics Technology Co., Ltd (HZC)
  - The production line imported from PHOTONIS France
- Mass production
  - Start: January 2018
  - End: December 2019
  - ~ 1,000 per month
  - 26,000 XP72B22 PMTs



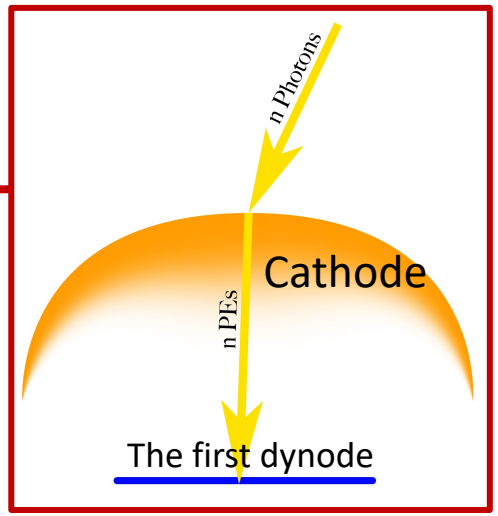
海南展创光电技术有限公司
HZC PHOTONICS

Performance Study of PMT Test Station

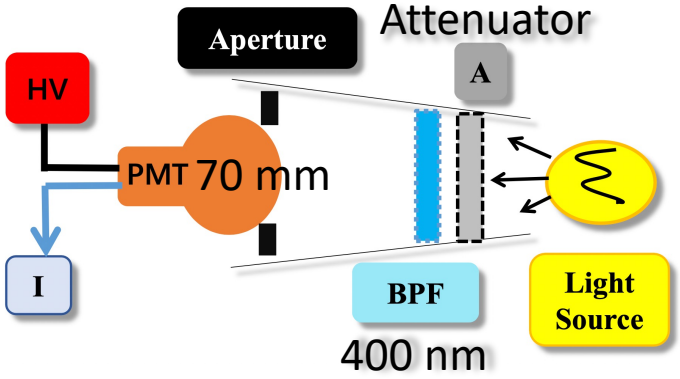
- 15 parameters have been characterized, team sent to HZC per ~ 3 months, HZC's facilities & manpower

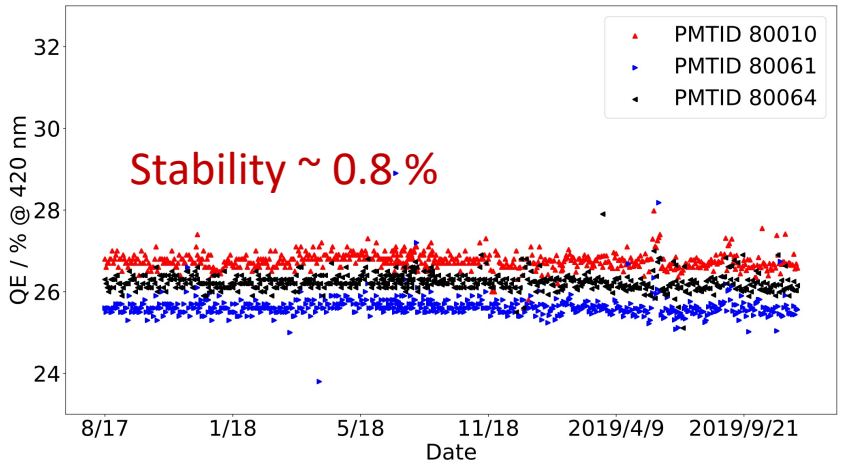
1. Static station (operated by HZC): testing quantum efficiency (QE) & high voltage (HV) at a nominal gain (3×10^6)
2. Single photoelectron (SPE, operated by HZC) station: testing SPE resolution, peak to valley (PV) ratio, dark count rate (DCR)
3. Transit time spread (TTS, operated by JUNO): testing TTS, pre-pulse, after-pulse
4. Scanning station (operated by HZC): testing QE non-uniformity & the effective diameter of the cathode

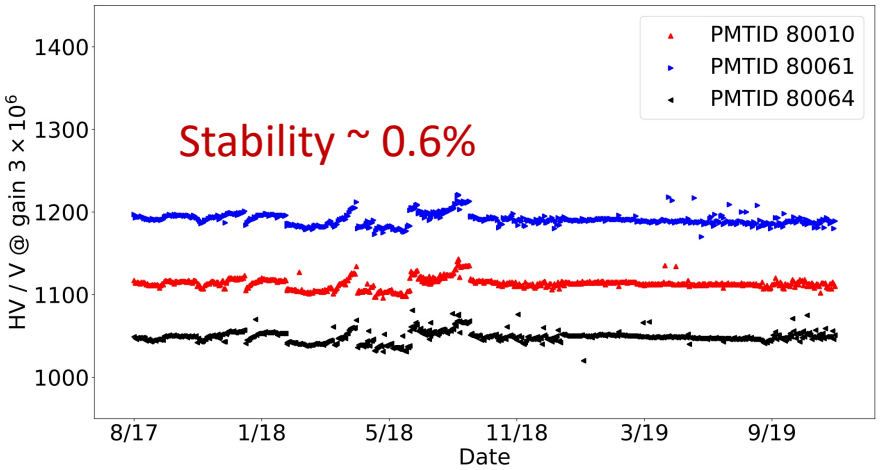
Static Station



- Relative QE
  - Reference PMT calibrated by a photodiode
  - $QE = \frac{I_k}{I_{kc}} QE_c$
    - I_k: The first-dynode current
    - QE_c: QE of reference PMT
    - I_{kc}: The first-dynode current of reference PMT
- HV @ 3×10^6 Gain
  - $G = \frac{I_a}{I_k} A$
    - G: Nominal gain
    - I_a: Anode current
    - A: Optical attenuator
    - I_k: Measured w/o attenuation

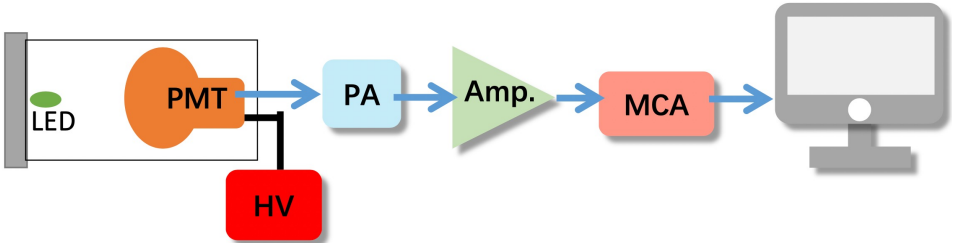


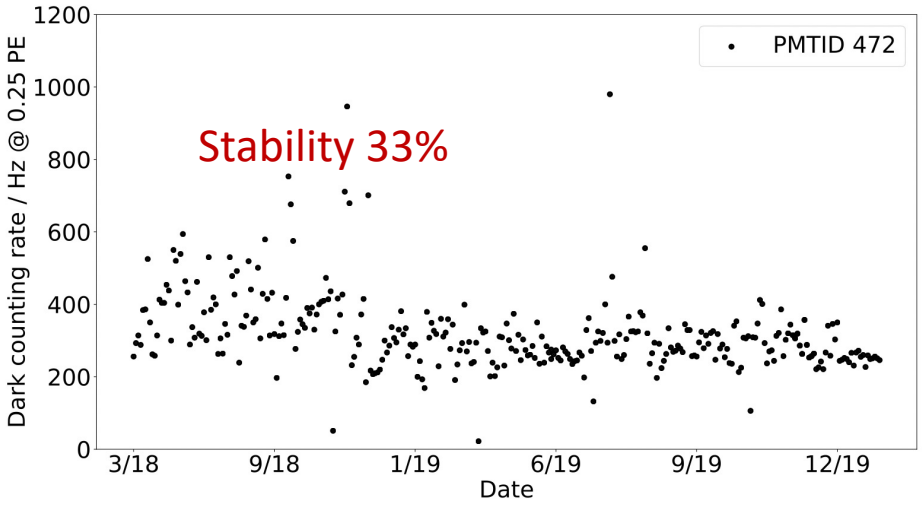


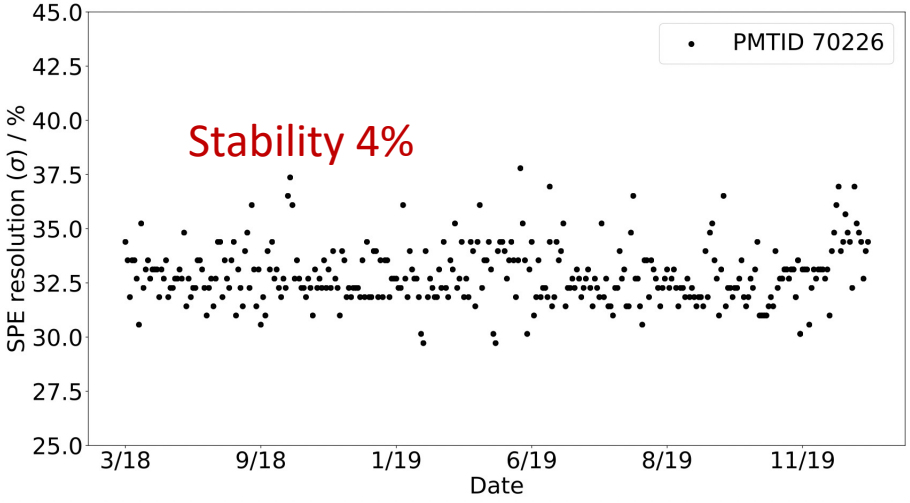


Single Photoelectron (SPE) Station

- SPE spectrum-related
  - SPE resolution
  - PV ratio
  - A monitor PMT
- DCRs
  - 0.25 PE threshold
    - Spontaneous thermal PE emission
  - 3 PE threshold
    - Electrical micro discharges
  - A monitor PMT

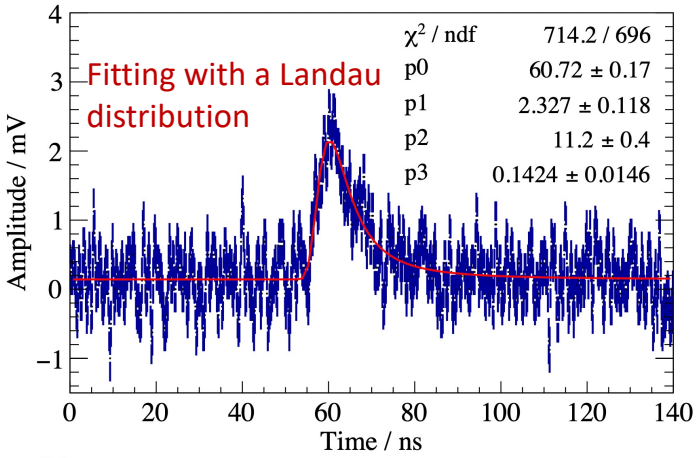


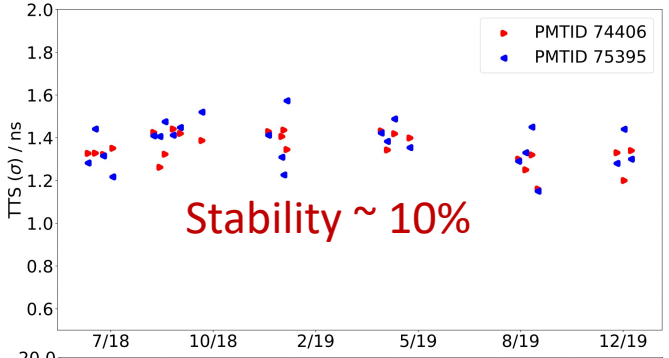




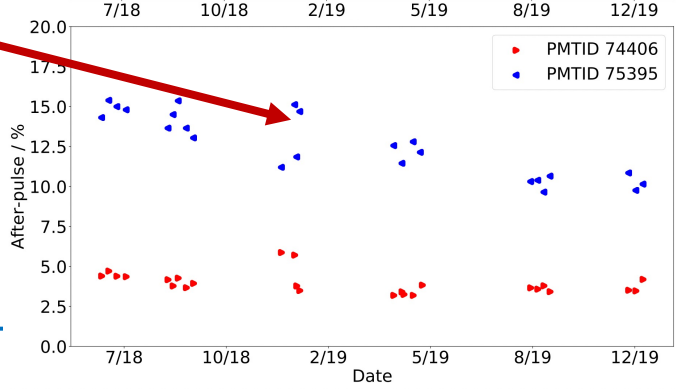
Transit Time Spread (TTS) Station

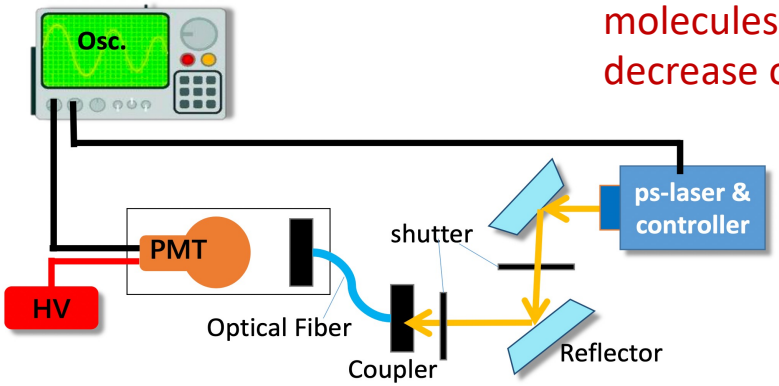
- TTS
  - Picosecond 405 nm laser
  - ~ 0.1 PE average light level
  - Two monitor PMTs
- Pre/After-pulse (with waveform)
  - ~ 100 PE average light level
  - Q_{main} = integration (-10, 15) ns
  - Q_{pre} = integration (-90, -10) ns
  - Q_{after} =integration (0.05, 20) μs
  - Two monitor PMTs





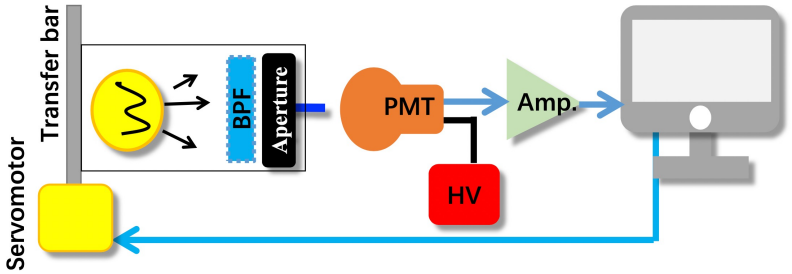
Ionization of residual gas molecules cause the decrease of 75395

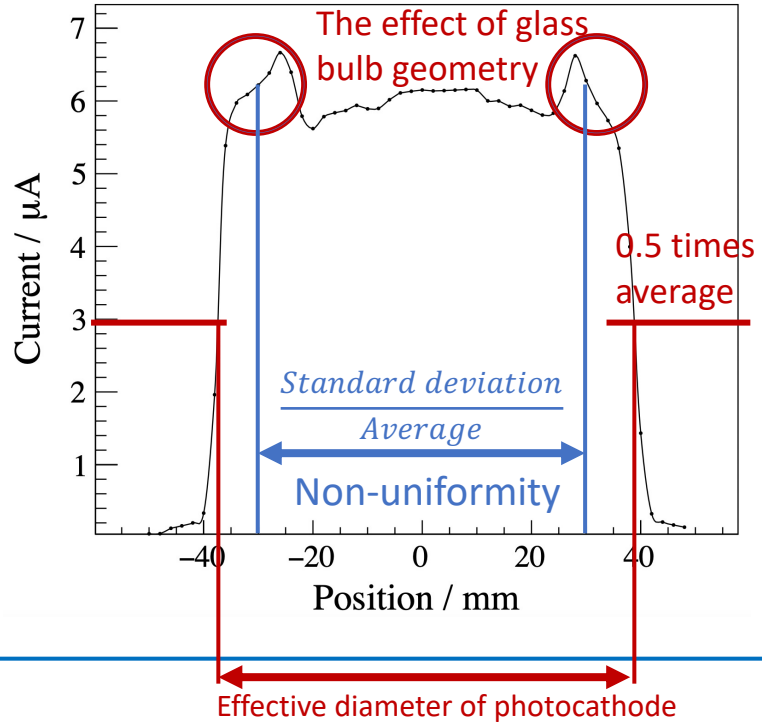


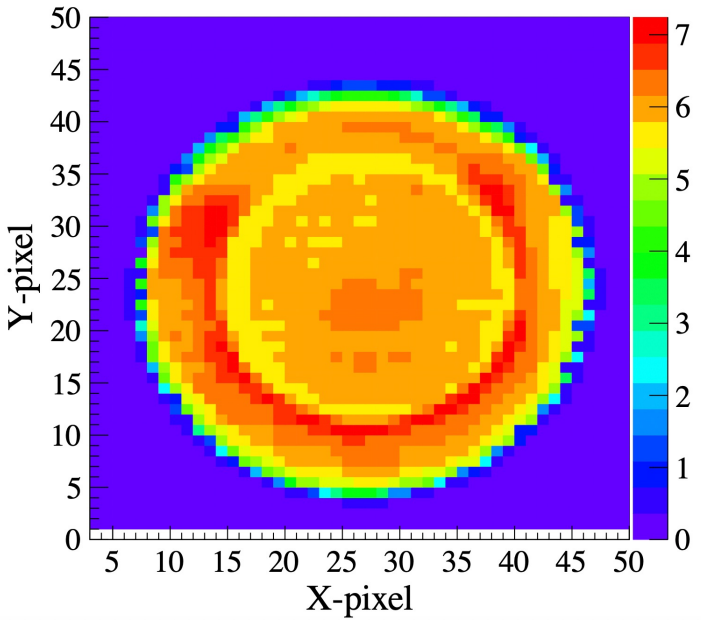


Scanning Station

- Non-uniformity of QE & Effective diameter of photocathode
  - A ~ 2 mm light spot
  - 2 mm step size
  - 100 * 100 mm^2 scanning range
  - 2500 pixels in total







Acceptance Test & Quality Assurance

- 15 parameters specified was divided into 4 classes according to

Parameters	Class	Test fraction	
		HZC	JUNO
Φ (glass bulb)	A	100%	10%
QE@420 nm	A	100%	10%
High Voltage	A	100%	10%
SPE resolution	A	100%	10%
PV ratio	A	100%	10%
DCR@0.25 PE	A	100%	10%
DCR@3.0 PE	A	100%	10%
TTS (σ)	B	-	3%
Pre-pulse	B	-	3%
After-pulse	B	-	3%
QE non-uniformity	B	-	3%
Φ (eff. cathode)	B	-	3%
QE@320 nm	C	-	1%
QE@550 nm	C	-	1%
Aging	D	-	3 PMTs

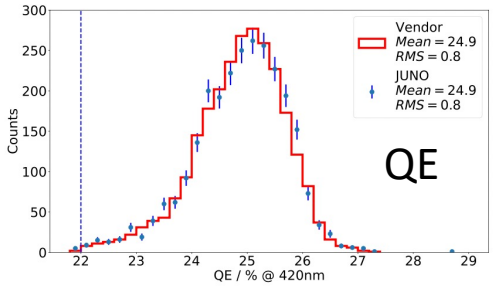
-Test stations
-Test time demands
-Products quality variation
-The importance to JUNO

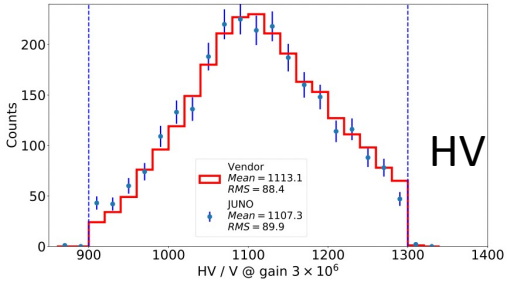
Compared and rejected PMTs with large discrepancy, then another 10% PMTs resampled

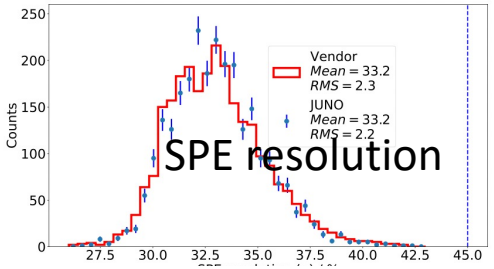
- All of the parameters were measured at 3×10^6 gain

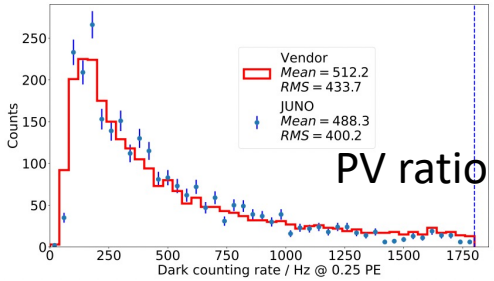
Class A Parameters

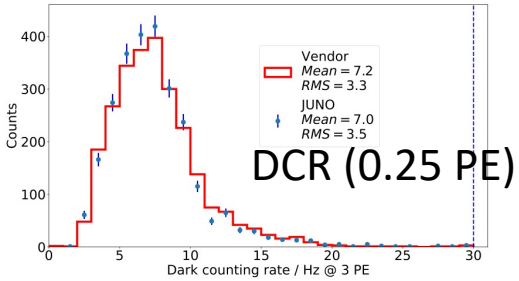
Good agreement between HZC data and JUNO sampling test data

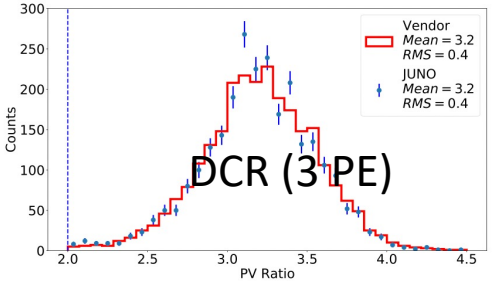


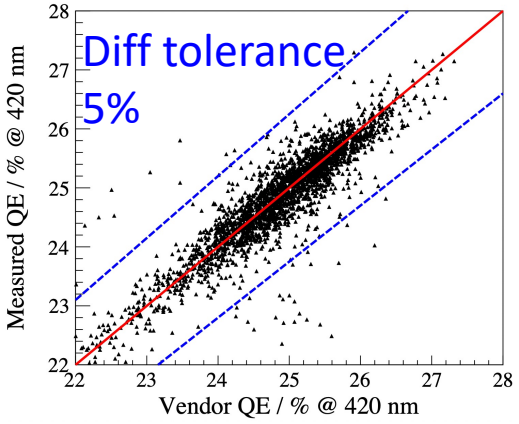


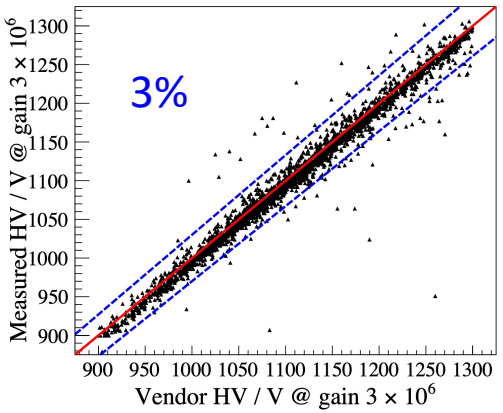


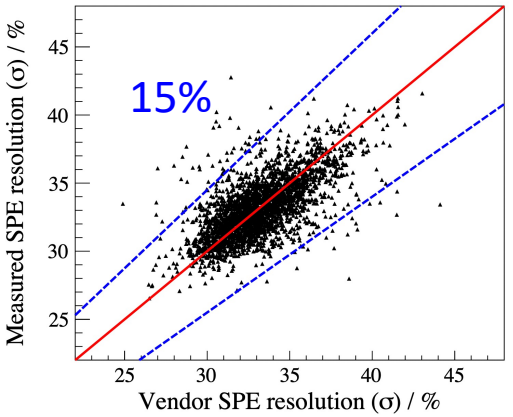








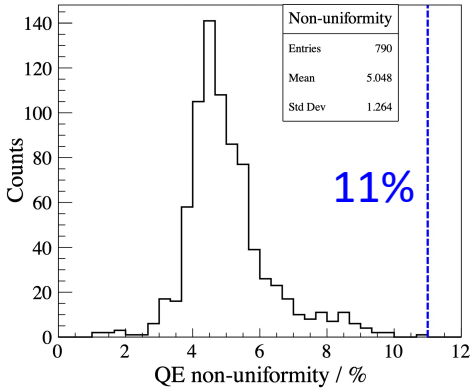


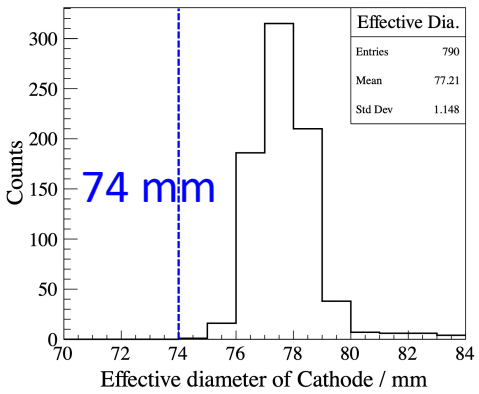


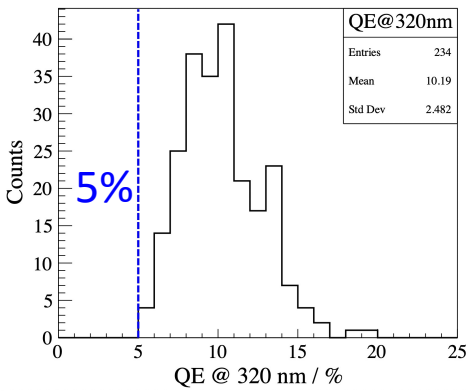
Class B & C Parameters

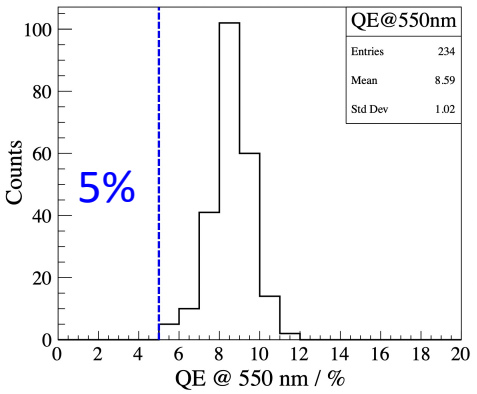
- B: 3%, PMTs through the class A test
- C: 1%, PMTs through the class B test

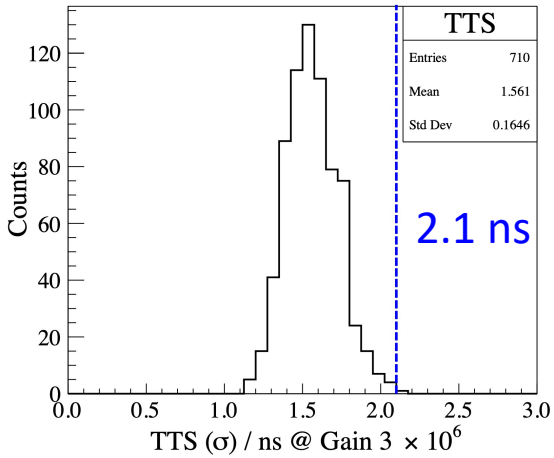
Parameters	Class	Requirement (limit)	(mean)
TTS (σ)	B	<2.1 ns	-
Pre-pulse	B	<5%	<4.5%
After-pulse	B	<15%	<10%
QE non-uniformity	B	<11%	-
Φ (eff. cathode)	B	>74 mm	-
QE@320 nm	C	>5%	-
QE@550 nm	C	>5%	-

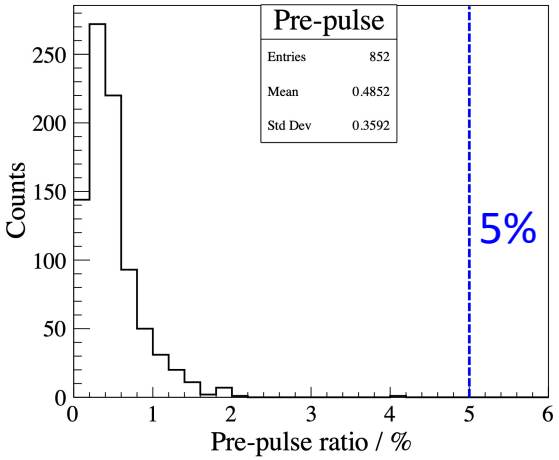


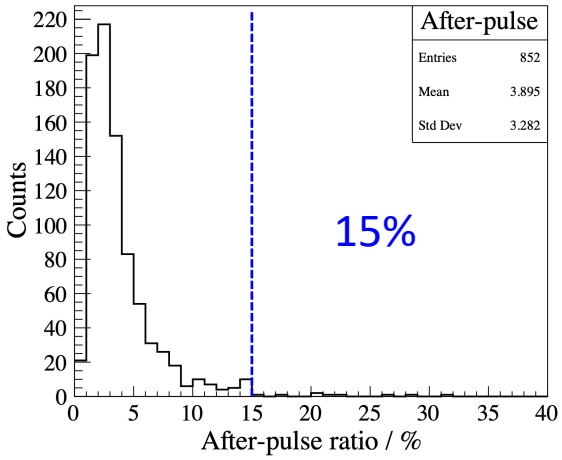






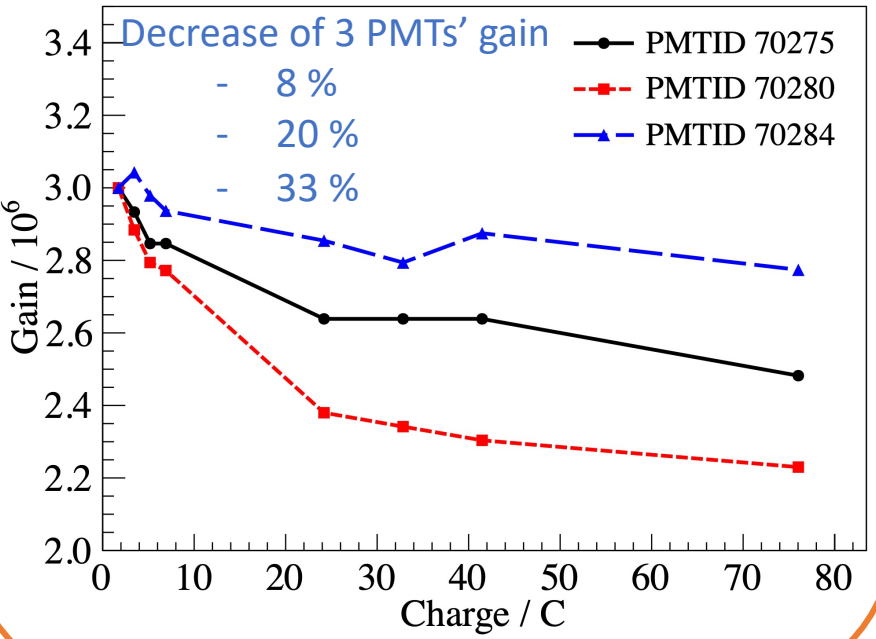




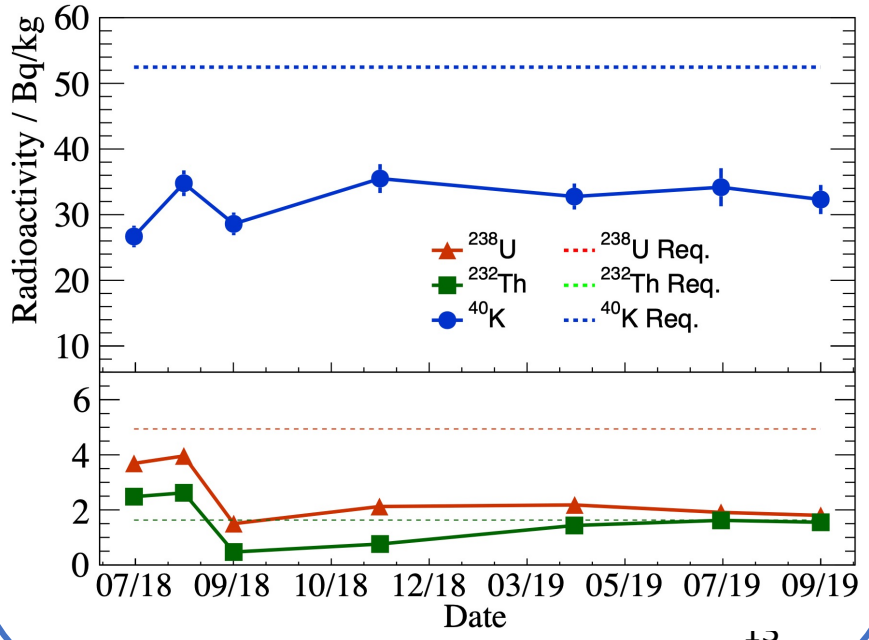


Aging (Class D) & Radioactivity monitoring

- 20 ~ 30 years of JUNO's operation, gain decrease < 50% required.
- 6.1 Coulombs (C) estimated accumulate charge in anode in 20 years.
- Total 76 C tested, ~ 10 times JUNO



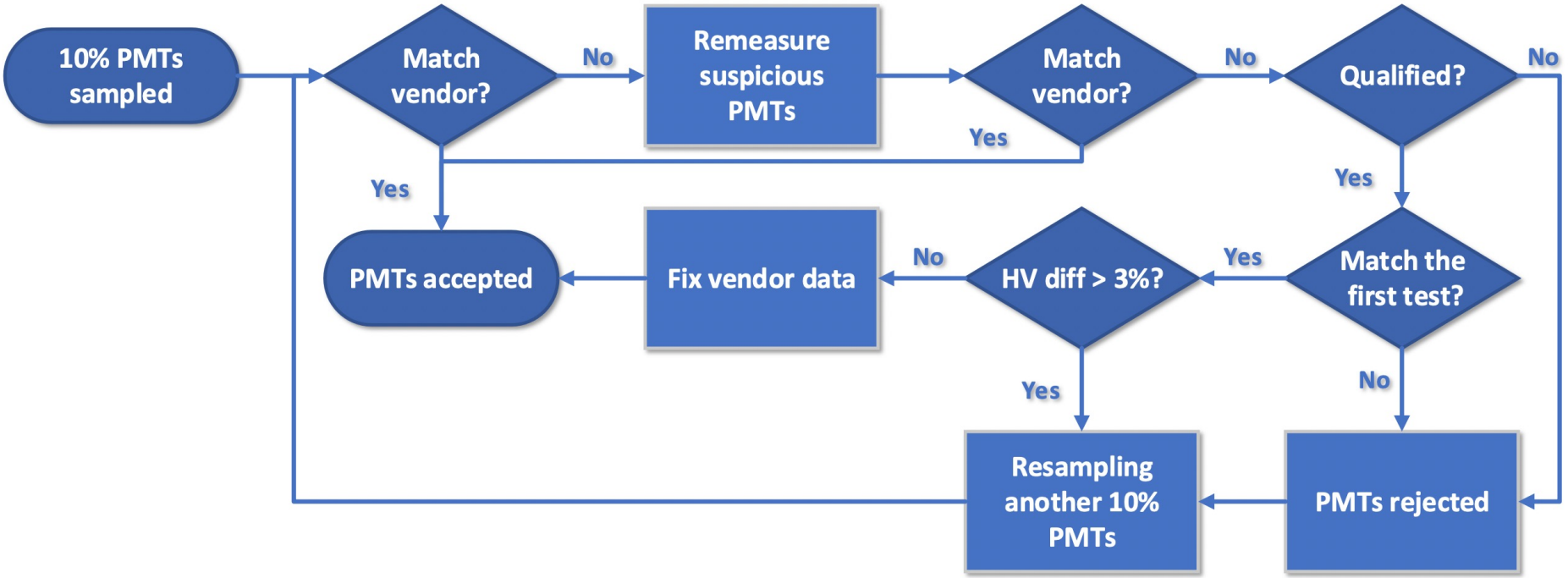
- Radioactivity measured per ~ 3 months
- all met requirements except ^{232}Th in the first two batches. Improved after better control of the environment cleanness.



Summary

- 3-inch PMTs will work as an independent photon detection system in JUNO
- All 26,000 PMTs were produced and characterized
  - 15 performance parameters tested at 4 stations
  - Test results comparison between HZC and JUNO for quality assurance
  - Only 15 PMTs rejected
- Waterproof sealing is ongoing and PMT installation in the JUNO detector will start in the end of 2021
- Paper: Mass production and characterization of 3-inch PMTs for the JUNO experiment, Nuclear Inst. and Methods in Physics Research, A 1005 (2021) 165347

Backup

Parameters	Class	Requirement (limit)	Requirement (mean)	Test fraction HZC	Test fraction JUNO	Tolerance of diff.	Results (mean)	Rejection number
Φ (glass bulb)	A	(78, 82) mm	-	100%	10%	-	OK	0
QE@420 nm	A	>22%	>24%	100%	10%	<5%	24.9%	1
High Voltage	A	(900,1300) V	-	100%	10%	<3%	1113 V	1
SPE resolution	A	<45%	<35%	100%	10%	<15%	33.2%	0
PV ratio	A	>2	>3	100%	10%	-	3.2	0
DCR@0.25 PE	A	<1.8 kHz	<1.0 kHz	100%	10%	-	512 Hz	1
DCR@3.0 PE	A	<30 Hz	-	100%	10%	-	7.2 Hz	1
TTS (σ)	B	<2.1 ns	-	-	3%	-	1.6 ns	0
Pre-pulse	B	<5%	<4.5%	-	3%	-	0.5%	0
After-pulse	B	<15%	<10%	-	3%	-	3.9%	11
QE non-uniformity	B	<11%	-	-	3%	-	5%	0
Φ (eff. cathode)	B	>74 mm	-	-	3%	-	77.2 mm	0
QE@320 nm	C	>5%	-	-	1%	-	10.2%	0
QE@550 nm	C	>5%	-	-	1%	-	8.6%	0
Aging	D	>200 nA·years	-	-	3 PMTs	-	OK	0

Class A acceptance test procedure